Data and Analytics Extra Info: GMLC Sensors and Measurement Roadmapping Activity

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Grid Modernization Laboratory Consortium

PROJECT 1.2.5: SENSING & MEASUREMENT STRATEGY

TASK 2: TECHNOLOGY ROADMAP DEVELOPMENT Technology Roadmap Slides: 3/27/2017 Draft

First Draft Submission to DOE for April 1st, 2017 Milestone

DESCRIPTION OF CONTENT:

These slides represent the first draft Technology Roadmap for the GMLC 1.2.5 Sensing & Measurement Strategy project that is due to DOE for review and comment on or before April 1st, 2016. This content is being developed by a broad team spanning the DOE national laboratory system as described in more detail in the project fact sheet with strong input and engagement from utilities and other industry stakeholders. Additional information and a list of references can be found in the corresponding Technology Review & Assessment Document developed and submitted to DOE on 9/30/2016.

CONTEXT FOR DISTRIBUTION:

The content within this draft will be refined and improved moving into future project years through strategic engagements with technical subject matter experts, utilities, and other stakeholder partners. Stakeholders are encouraged to send along detailed feedback and suggestions directly to Paul Ohodnicki (paul.ohodnicki@netl.doe.gov), Task 2 Roadmapping Activity Lead and Sensing & Measurement Project Co-PI as well as Tom Rizy (dtom@ornl.gov) , Sensing & Measurement Project PI.

DOE LABORATORY CONTRIBUTORS:

Paul Ohodnicki (NETL), Tom Rizy (ORNL), Chen Chen (ANL), Olga Lavrova (SNL), Philip Top (LLNL), Emma Stewart (LLNL), Jeffrey Taft (PNNL), Yarom Polsky (ORNL), Felipe Bernal-Wilches (SNL), Andrew Clifton (NREL), Matthew Lave (NREL), Zhi Li (ORNL), Guodong Liu (NREL), Peter Fuhr (ORNL), Steven Bossart (NETL), Michael McElfresh (ANL), Thomas King (ORNL)

Technology Roadmap Development Process to Date

Project Year 1	Project Year 2	Project Year 3
Develop Initial Draft of a Technology Review Assessment Document for DOE. (Due: 9/30/2016) Develop an initial Roadmap Document Incorporating Stakeholder Feedback & Input. (Due: 4/1/2017)	Improve Integration of Roadmap Documents with Extended Grid State Definition. Establish Working Groups to Further Develop Roadmap Content within Each Identified Focus and Thrust Area Including Gap Analysis. Hold an Annual Stakeholder Meeting to Discuss and Provide Feedback. Refine, Revise, and Update Roadmap and Technology Assessment Documents. (Due: 4/1/2018)	Further Develop Roadmap Content within Each Identified Focus and Thrust Area Including Gap Analysis. Hold an Annual Stakeholder Meeting to Discuss and Provide Feedback. Refine, Revise, and Update Roadmap and Technology Assessment Documents. (Due: 4/1/2019)

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Organizing the Technology Roadmap

Low cost **sensing**, **communication**, and **data management** solutions that meet the needs of a future modernized electricity grid

Modernized Electrical Grid That Balances Six Attributes:
Reliable
Secure
Affordable
Flexible
Resilient
Sustainable

1 ELECTRICAL STATE
2 TOPOLOGICAL STATE
3 COMPONENT STATE
4 BUILDING STATE
5 AMBIENT STATE
6 CONVERGENT NETWORK STATES

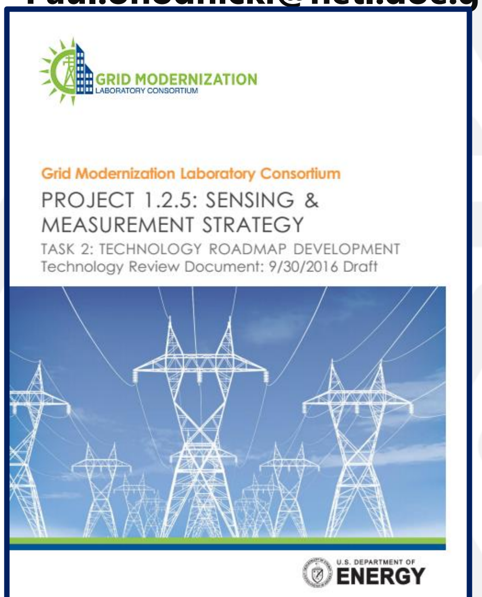
Mission **Drivers** **Visibility of Extended Grid State**

Initial Review Draft Development → Organize Based on (Devices, Communications, Data Management & Analytics) and Application Domains Consistent with 1.4.4 Sensor Development Project

Ultimate Goal → Map Research Thrusts / Focus Areas to Needs Identified by the Extended Grid State Definition

Technology Review and Assessment Document

Devices	Communications	Data Management / Analytics
Coordinator: **Paul Ohodnicki, NETL** **Paul.ohodnicki@netl.doe.go**	**Coordinator:** **Chen Chen, ANL** **morningchen@anl.gov**	**Coordinator:** **Phillip Top, LLNL** **top1@llnl.gov**


GRID MODERNIZATION
LABORATORY CONSORTIUM

Grid Modernization Laboratory Consortium
PROJECT 1.2.5: SENSING & MEASUREMENT STRATEGY
TASK 2: TECHNOLOGY ROADMAP DEVELOPMENT
Technology Review Document: 9/30/2016 Draft

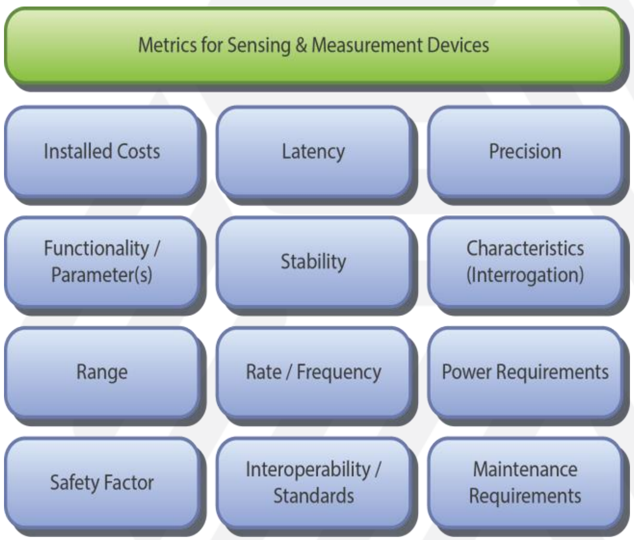
U.S. DEPARTMENT OF ENERGY

Application Domains Aligned with Sensor Development 1.4.4 Project

- **Conventional Generation Sensing for More Flexible Operation**
- **Renewable Generation Sensing and Weather Monitoring**
- **T&D System Power Flow and Grid State Monitoring**
- **Asset Monitoring and Fault Diagnosis**
- **End-Use / Buildings Monitoring for Responsive Loads**

High-Level Findings of the Technology Review

Cross-cutting Findings Spanning the Application Domains



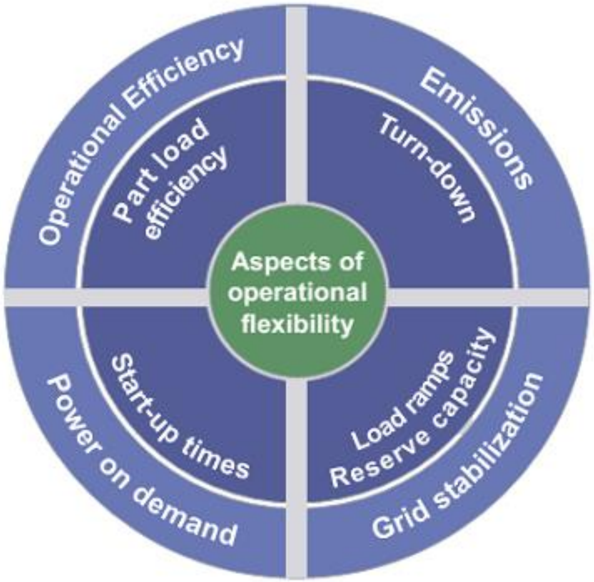
(1) Needs exist for advanced instrumentation at centralized generation and transmission levels, but a relative lack of visibility exists within the distribution system.

(2) The “per unit” value of a comparable sensor installed and deployed on the distribution system or at the end-user level is dramatically lower than the corresponding transmission level. Enhancing visibility in the distribution system and at the end-user level requires advances in (1) low-cost and (2) multi-function or multi-parameter sensors.

(3) Standards and interoperability will be an important aspect of new sensing and measurement device development and deployment.

High-Level Findings of the Technology Review

Conventional Generation Sensing for More Flexible Operation



Harsh-environment instrumentation relevant for conventional thermal-based generators (fossil, nuclear, etc.) could help to enable more flexible operation and minimize long-term impacts of cycling and ramping on plant longevity and efficiency.

Capabilities of existing automatic generation controllers (AGC) and associated sensing and measurement devices should be evaluated in terms of the potential for new technology innovations.

High-Level Findings of the Technology Review

Renewable Generation Sensing and Weather Monitoring

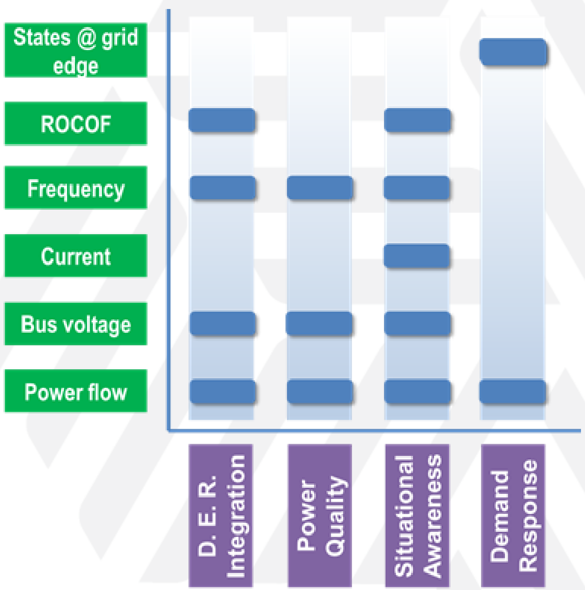
States/Parameters	Directly measured or calculated from measurements	Sensors/meters required	Description and Note
For wind energy			
Wind speed	Measured	Anemometers or lidar remote wind sensors	Measures the resource available for wind turbines
Air temperature	Measured	Thermocouples	Impacts turbine performance year-round, can indicate risk of plant shutdown for icing
Power (per turbine)	Measured	Current and voltage transducer or PMUs	Measured at the turbine bus bars
Power (plant)	Measured	Current and voltage transducer or PMUs	Measured at point of revenue metering
For solar energy			
Irradiance (GHI)	Measured	Pyranometers*	Measures the resource available for the system but needs to be transformed to the plane of array
Irradiance (plane of array)	Measured	Pyranometers,reference cells**	Measures the resource available for panels
Air temperature	Measured	Thermocouples	Second-order impact on panel performance
Cloud motion	Measured	Satellites or total sky imagers	Used for real-time and short-term power prediction
Power (per panel)	Measured	Power transducer or inverter	
Power (plant)	Measured	Point of revenue metering	

Weather monitoring and forecasting technologies exist at high technology readiness levels (TRL) for predicting renewable generation (solar, wind, etc.), and innovations often involve adaptation of mature sensing technology developed in other fields.

Emerging trends include data management and application of unmanned aerial vehicles and lidar-based techniques.

High-Level Findings of the Technology Review

T&D System Power Flow and Grid State Monitoring



Do you understand the difference between phasors and synchrophasors? The difference has significant implications.

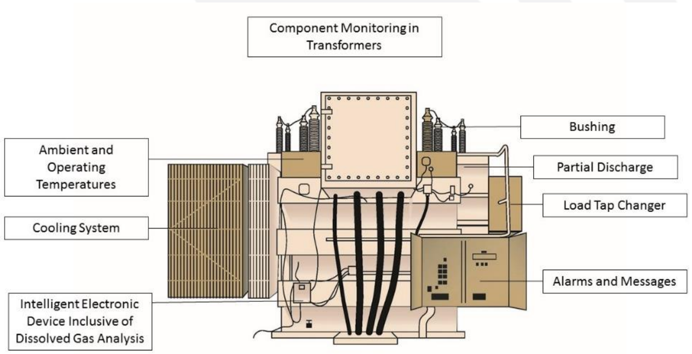
Phas… logy for power flow and grid state … nain for improvements in reliability, speed, accuracy, cost, and their applications at distribution level.

Yes the team understands the difference. If you have specific feedback about a change requested, specify explicitly rather than asking questions which require interpretation of intent to address.

Emergi… based current and voltage transdu… for new innovations.

High-Level Findings of the Technology Review

Asset Monitoring and Fault Diagnosis



Asset monitoring of electrical grid assets can be classified into both “functional performance” and “health monitoring” with the former requiring predominantly electrical parameter sensors and the latter requiring sensors for a broad range of parameters such as temperature, chemistry, and strain.

Sensor instrumentation exists for established grid components, but costs currently limit deployment to the most critical assets. Also, new sensing technologies are required for emerging grid components and faster (near-real-time or dynamic) monitoring and controls.

High-Level Findings of the Technology Review

End-Use / Buildings Monitoring for Responsive Loads

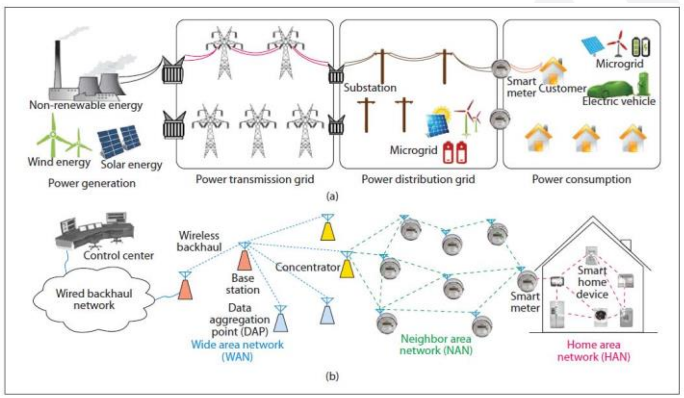
States/Parameters	Directly measured or calculated from measurements	Phasor or scalar	Sensors/meters required	Description and Note
Nodal voltage	Measured	Phasor	VT	Measured by smart meter only
Nodal current	Measured	Phasor	CT	Measured by smart meter only
Frequency	Calculated	Scalar	FNET Devices	Calculated by smart meter only
Real power	Measured/Calculated	Scalar	PQNode, Smart Meters	Measured by electromechanical meters/ Calculated by smart meter
Reactive power	Calculated	Scalar	PQNode	Calculated by smart meter only
Power factor	Calculated	Scalar	PQNode	Calculated by smart meter only
Power quality	Calculated	Scalar	PQNode	RMS voltage, THD and phase balance
Temperature	Measured	Scalar	Thermometer	Measured
Luminance	Measured	Scalar	Illuminometer	Measured
Indoor air quality sensor	Measured	Scalar	Integrated health sensor	Measured CO2,H2O,etc.
Occupancy	Measure/Calculated	Scalar	Moving sensors	Measured by moving sensors or calculated with other measures

Trends of increased generation at residential and commercial scale as well as projections for widespread electric vehicle deployment require increased visibility at the load to enable demand response and transactive energy strategies.

Low-cost sensor technologies for monitoring power flow as well as parameters characteristic of the current and forecasted load will be of increasing importance.

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

High-Level Findings of the Technology Review



Communications

(1) A paradigm shift is anticipated toward broader implementation of distributed rather than centraliz Delete this slide. acterized by communications and intelligence at lower levels.

(2) Reduced latencies and robust peer-to-peer communications in addition to communication ntrol center will be of increasing impo

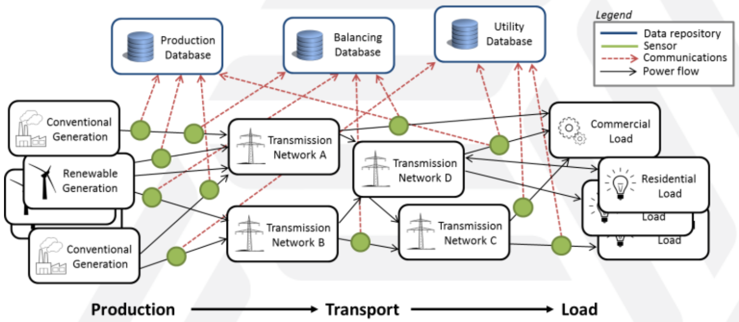
Communications is a required part of the project from the very beginning and cannot be eliminated. This slide comes directly from the technology review and all previous slide versions. If there are specific points in the text to be addressed show explicitly.

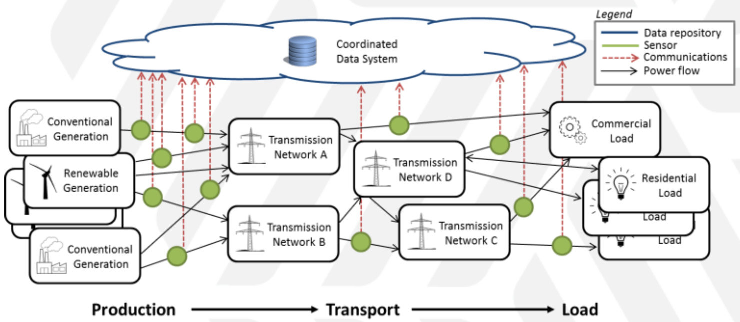
(3) A hierarchica ars highly desirable based upon several ke

- Scalab d measurement devices
- Flexibilit nd applications
- Efficienc erent communication technologies
- Reduced latency with more distributed data processing and control

High-Level Findings of the Technology Review

Data Management and Analytics





(1) The desire for dramatically increased visibility across the electricity grid infrastructure will necessarily increase the deployment of sensing and measurement devices and associated data management needs to unprecedented levels.

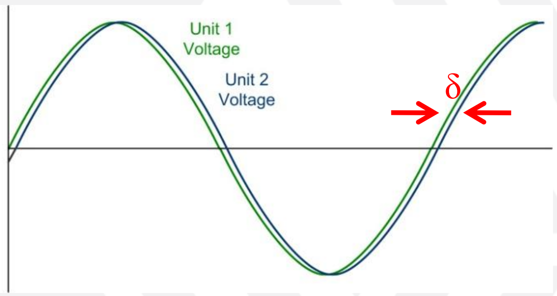
(2) A shift towards distributed data analytics methodologies rather than centralized approaches is a potentially key component of the required technical solution.

(3) For the existing sensing and measurement infrastructure, there remains a great amount of “value” yet to be extracted through advanced data management and analytics approaches especially at the distribution level, which has traditionally been limited to substation monitoring and control.

Extra Info – synchrophasors & distribution sychrophasors

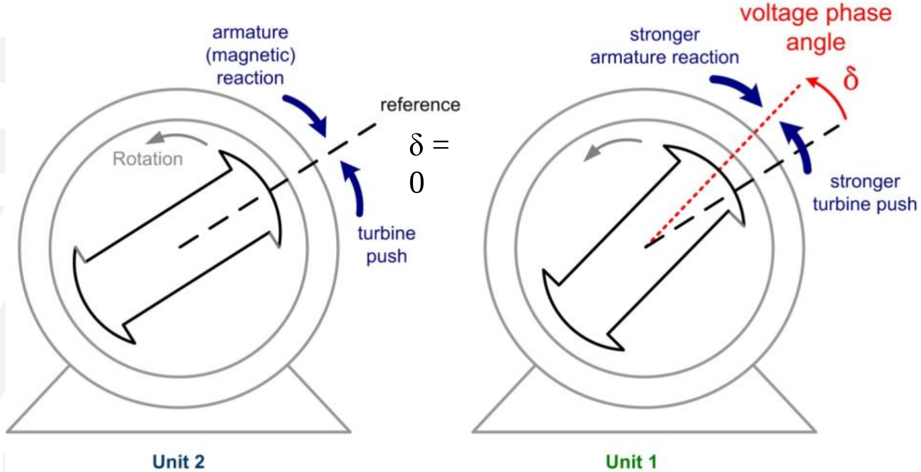
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Synchrophasors compare voltage phase angle at different locations



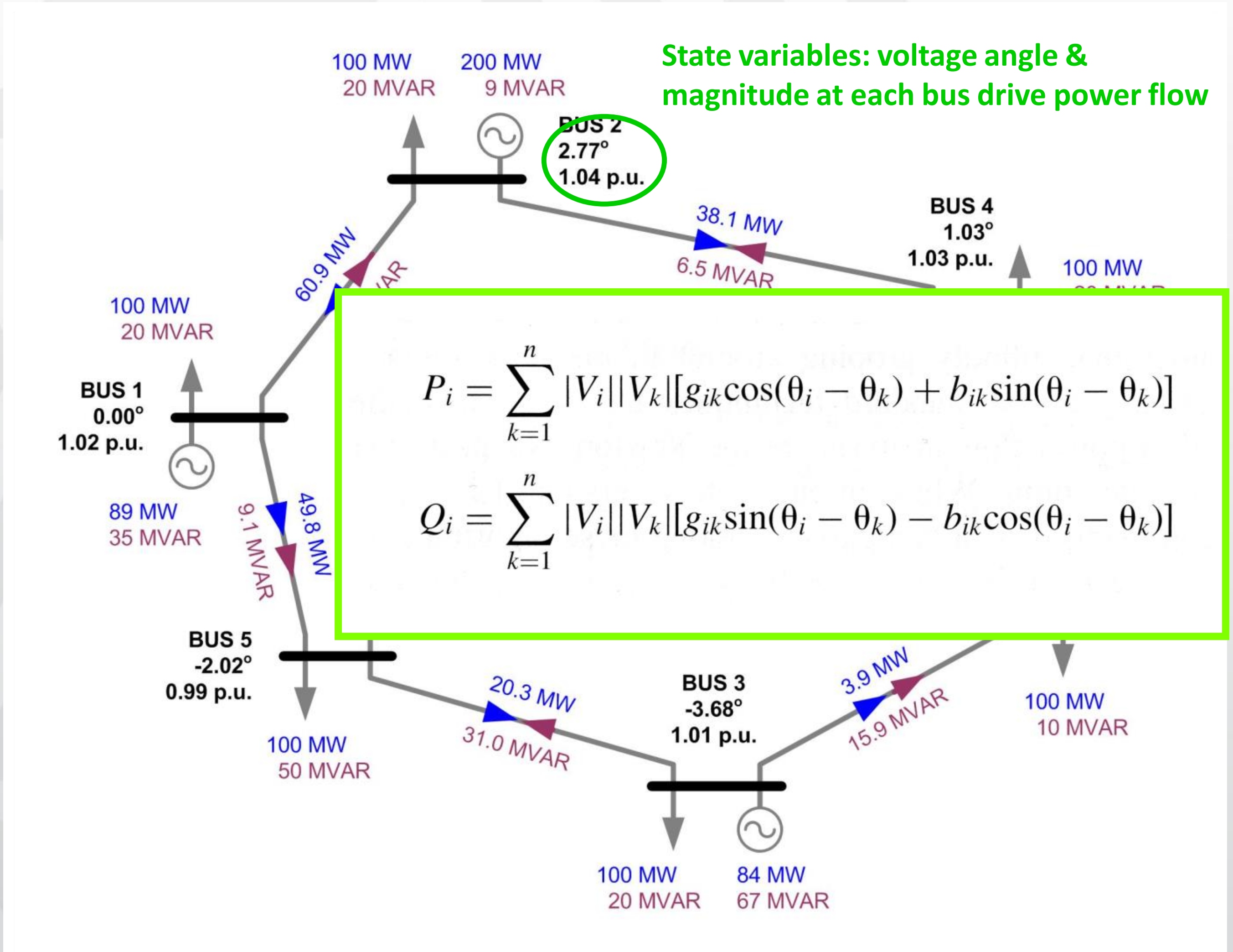
the small phase angle δ between different locations on the grid drives a.c. power flow

$$P \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$



power flows from Unit 1 toward Unit 2

State variables: voltage angle & magnitude at each bus drive power flow



$$P_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k)]$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\theta_i - \theta_k) - b_{ik}\cos(\theta_i - \theta_k)]$$

FINAL REPORT - SYSTEM DISTURBANCE ON 4 NOVEMBER 2006

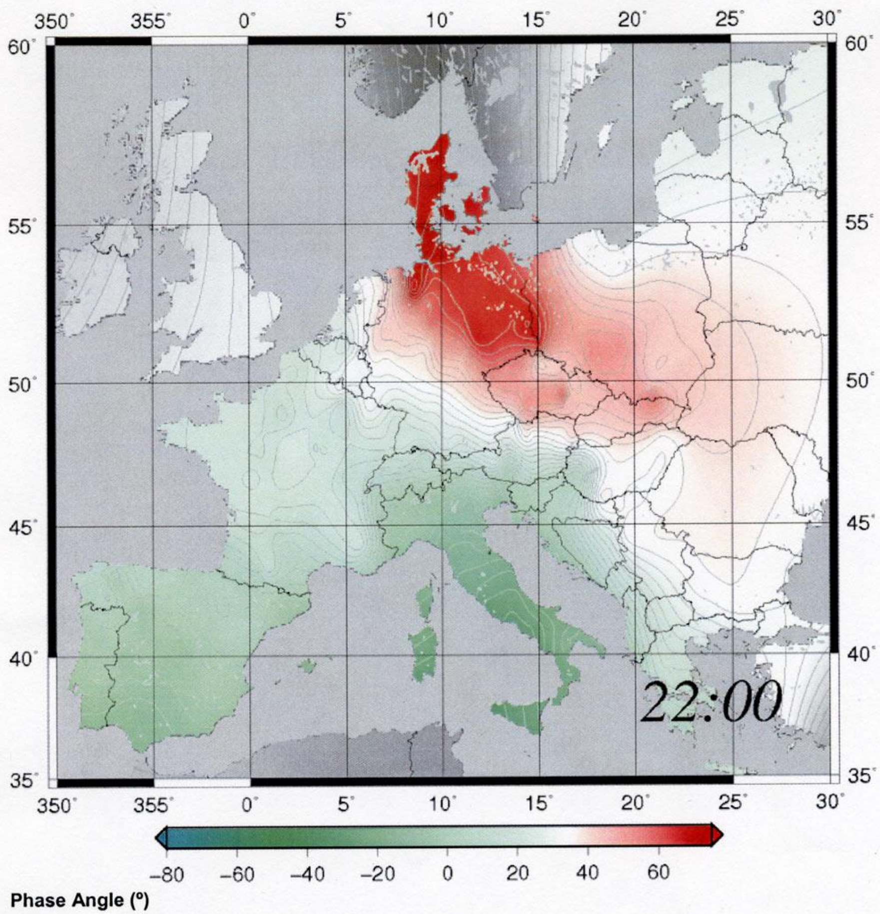
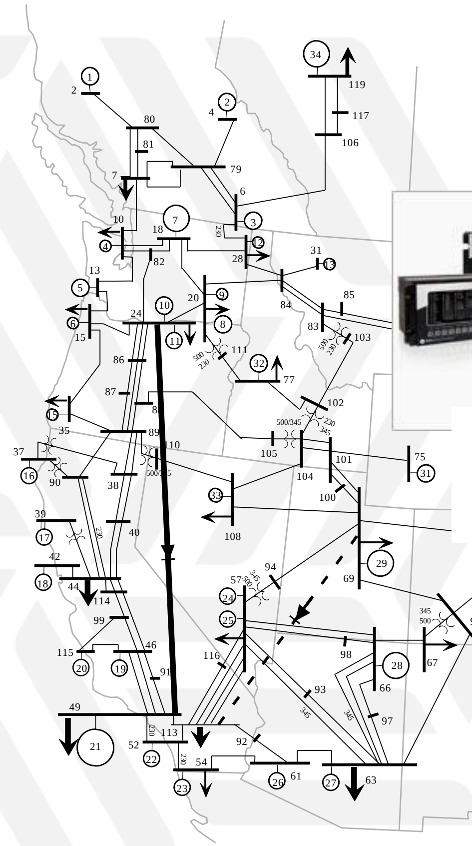
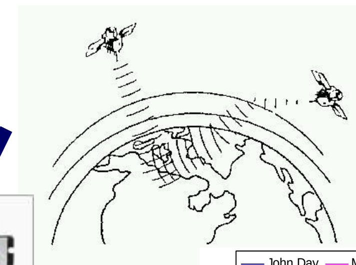


Fig. D1a: **Voltage phase angle differences in the UCTE system at 22:00 /ELES/**

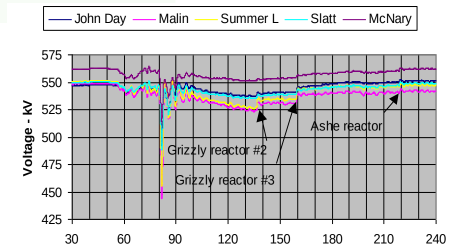
Voltage phase angles separating, just before a major blackout

Synchrophasors compare voltage phase angle at different locations

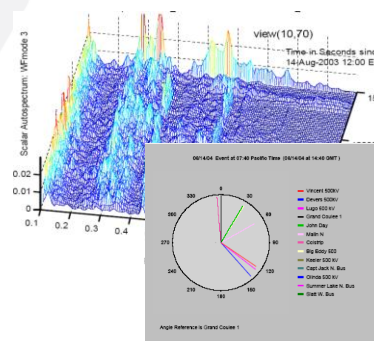




Phasor Measurement Units (PMUs)

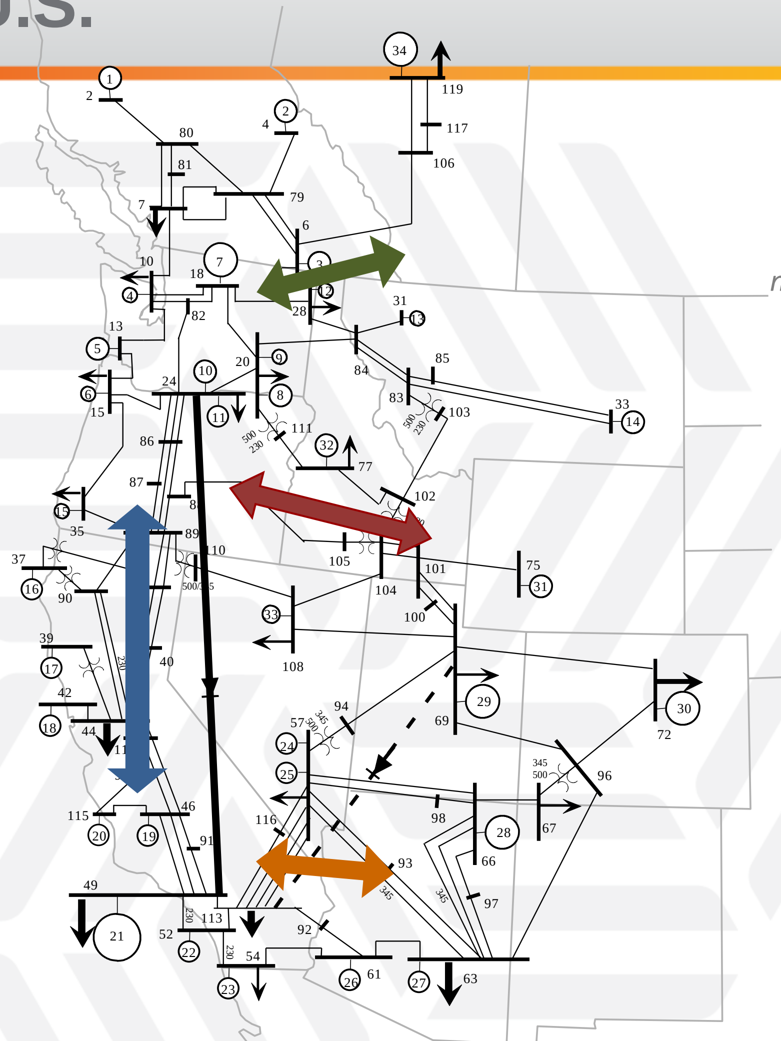


synchronous data



useful real-time information for system operators

Characteristic sub-synchronous oscillations impose significant transmission constraints in the Western U.S.



note: these oscillations existed before major renewables deployment

Alberta
0.45 Hz

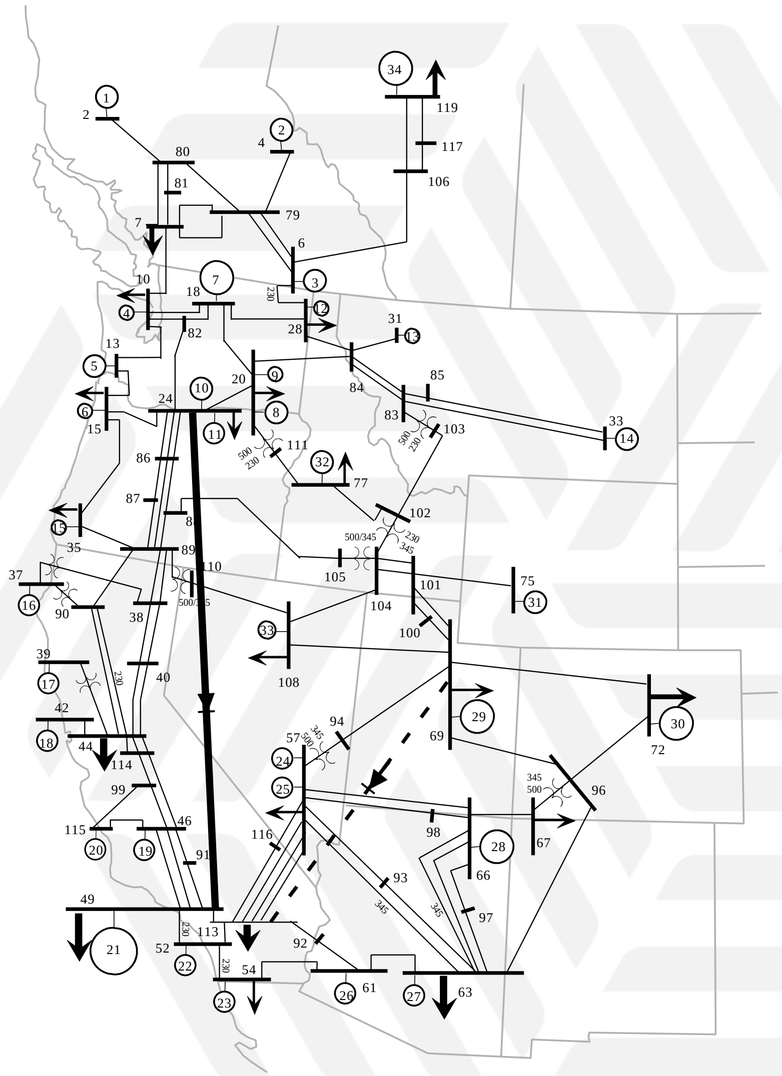
East-West
0.6-0.7 Hz

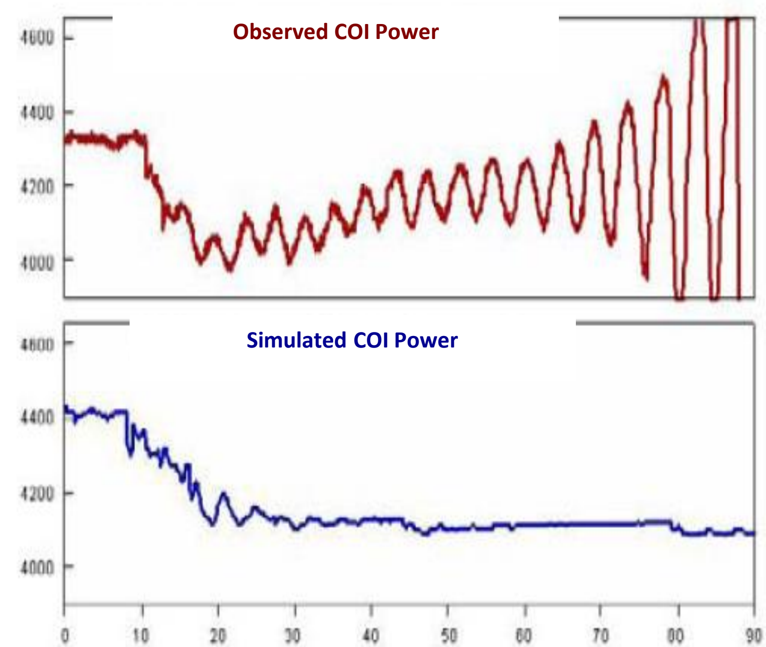
North-South
0.25-0.3 Hz

California-Desert
Southwest 0.5 Hz

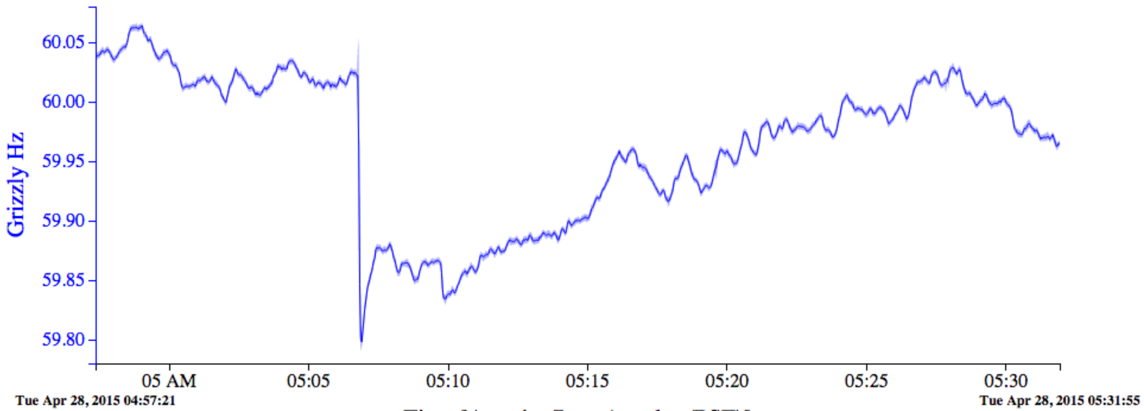
California-Oregon Intertie Aug 10, 1996 as seen with and without synchrophasors

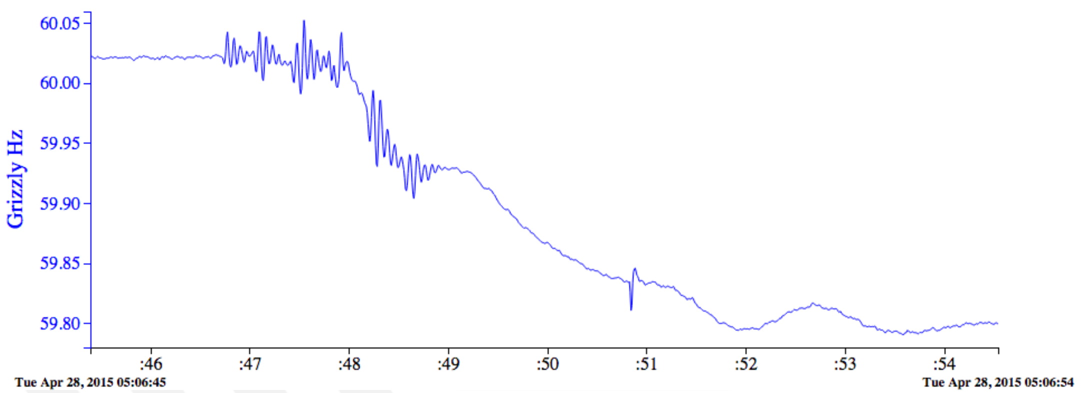
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy





Situational Awareness with μPMUs: Transmission system event at different time resolutions

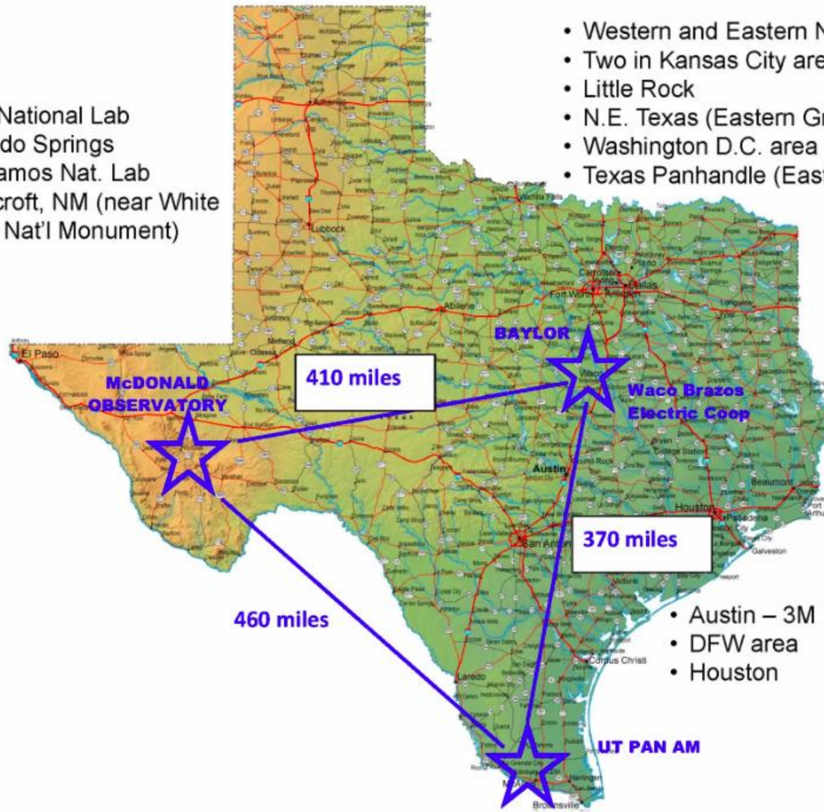




Texas Synchrophasor Network

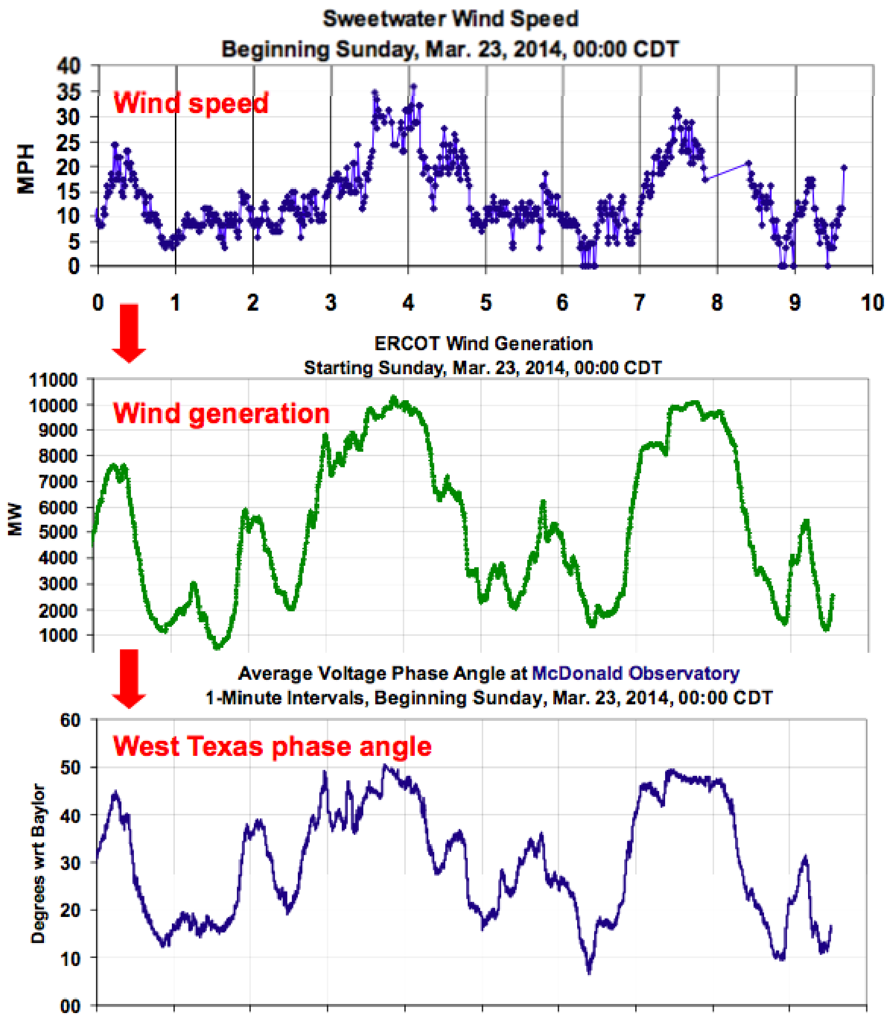
- Idaho National Lab
- Colorado Springs
- Los Alamos Nat. Lab
- Cloudcroft, NM (near White Sands Nat'l Monument)

- Western and Eastern Nebraska
- Two in Kansas City area
- Little Rock
- N.E. Texas (Eastern Grid)
- Washington D.C. area
- Texas Panhandle (Eastern Grid)



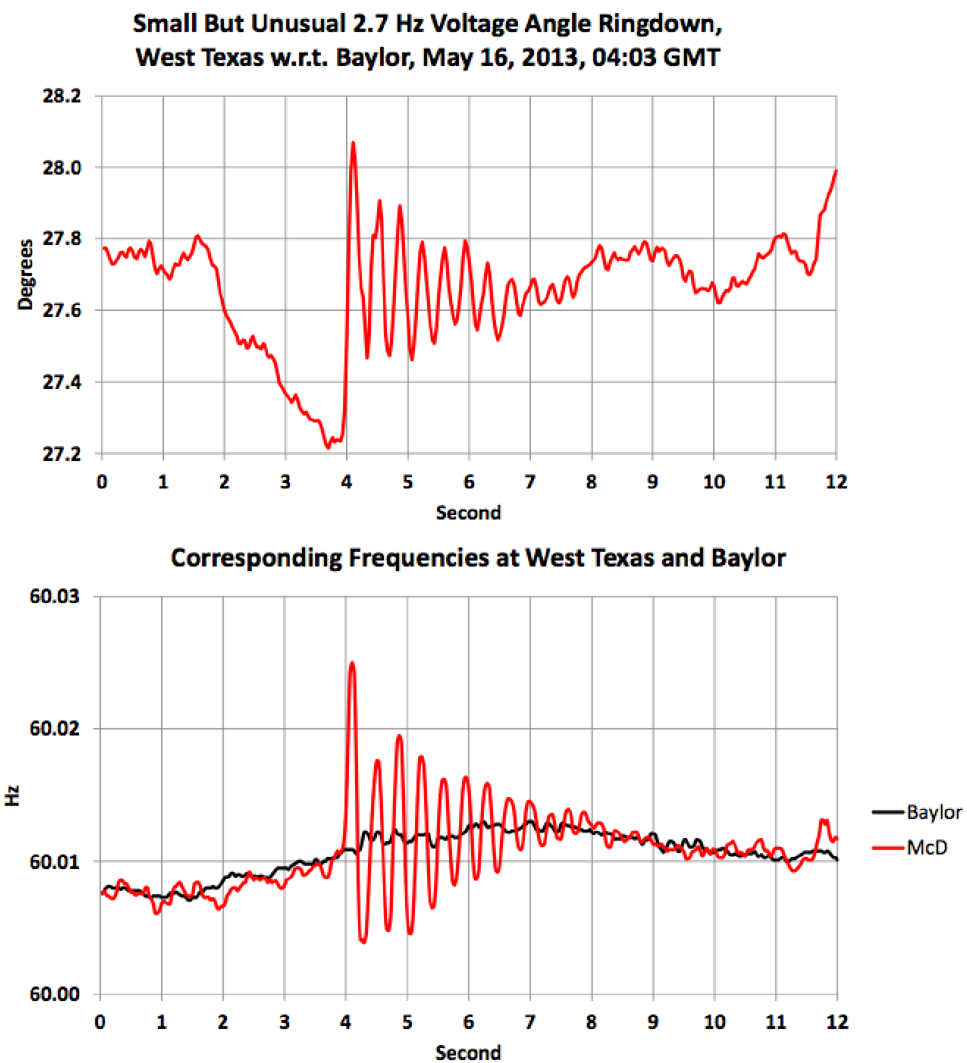
- Austin – 3M
- DFW area
- Houston

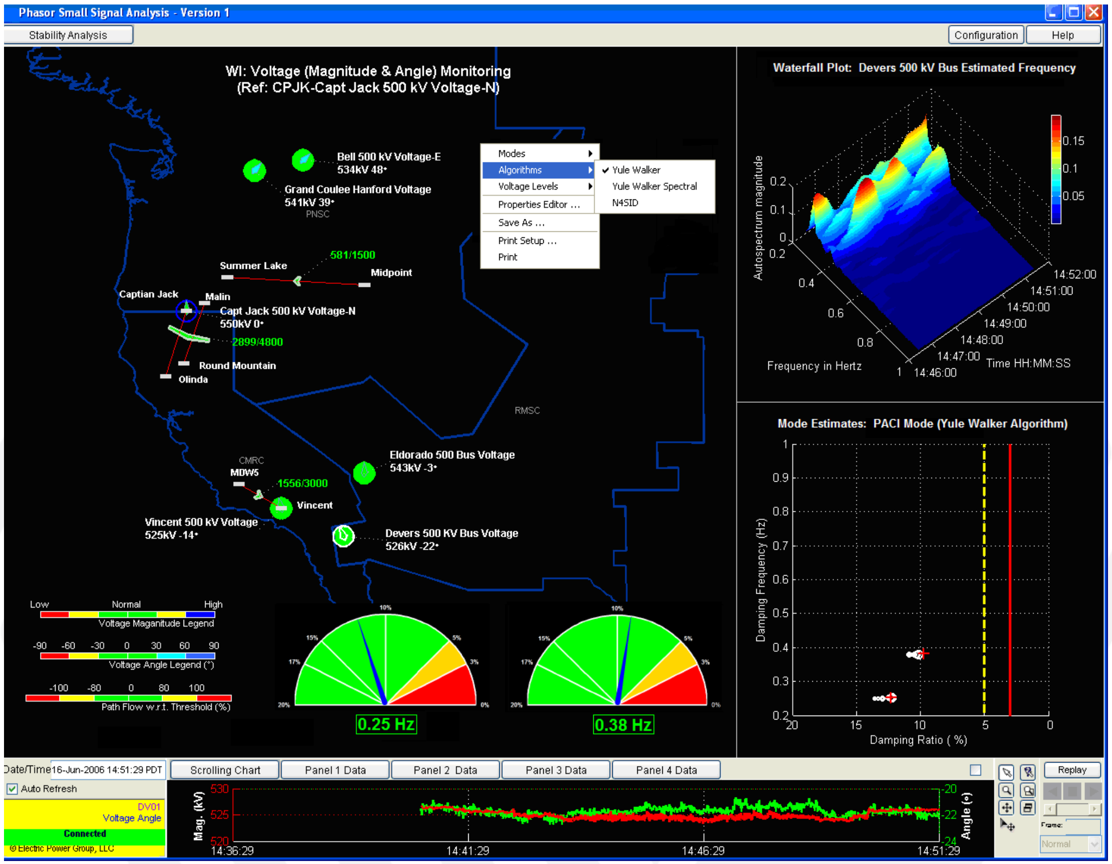
http://web.ecs.baylor.edu/faculty/grady/Texas_Synchrophasor_Network.html
looking at the transmission grid from distribution, behind the substation



Key Lesson for Today

If you need the loadflow voltage phase angle for West Texas, find out how fast the wind is blowing in Sweetwater


Small But Unusual 2.7 Hz Voltage Angle Ringdown,
West Texas w.r.t. Baylor, May 16, 2013, 04:03 GMT
Degrees
28.2
28.0
27.8
27.6
27.4
27.2
0 1 2 3 4 5 6 7 8 9 10 11 12
Second
Corresponding Frequencies at West Texas and Baylor
Hz
60.03
60.02
60.01
60.00
0 1 2 3 4 5 6 7 8 9 10 11 12
Second
Baylor
McD

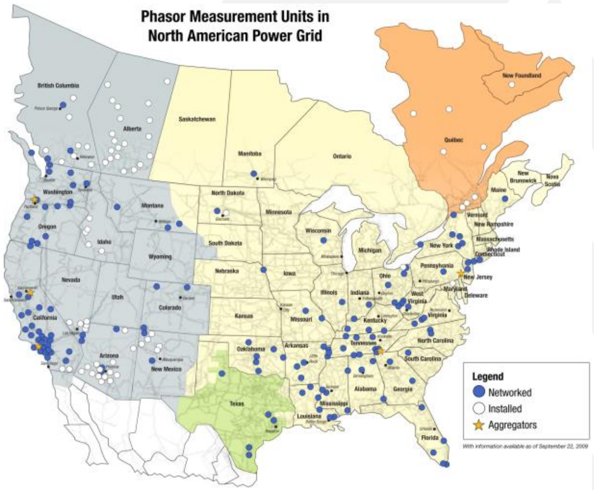


Courtesy
CERTS

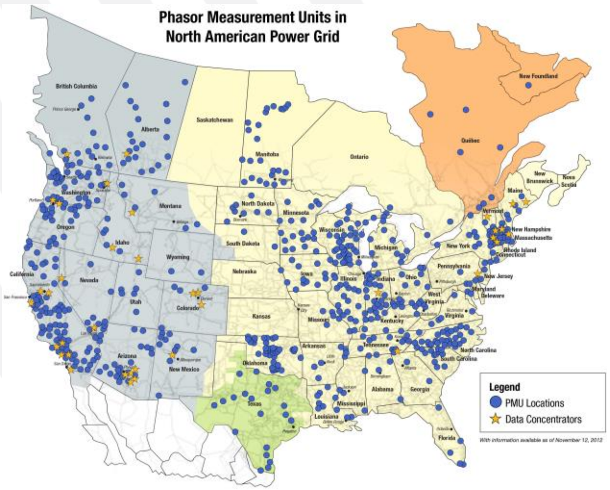
This application analyzes PMU data to show damping of characteristic sub-synchronous oscillation modes

PMU's in the US

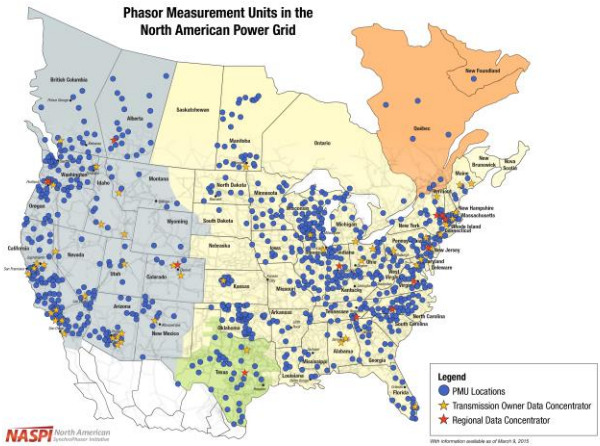
2010



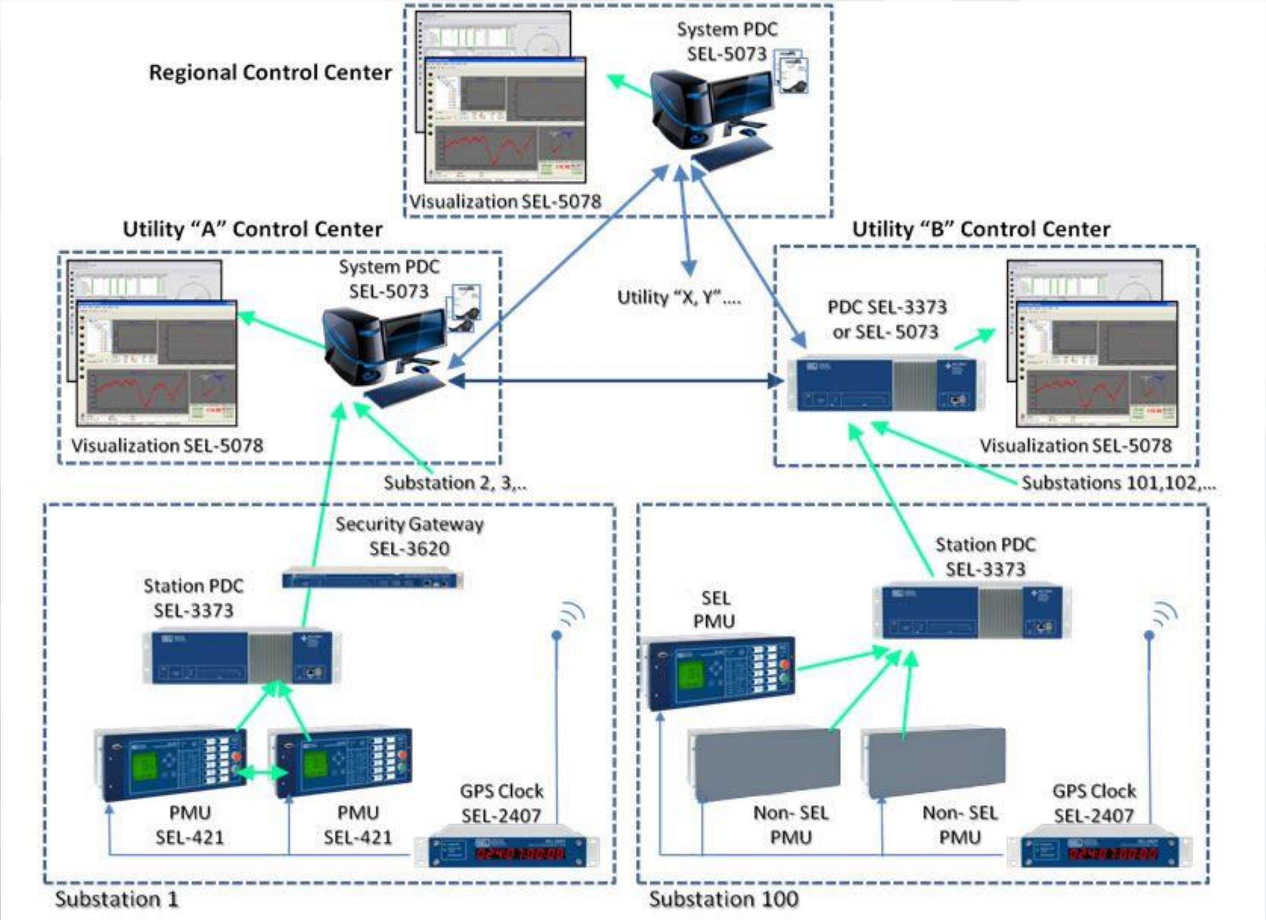
2012



2015



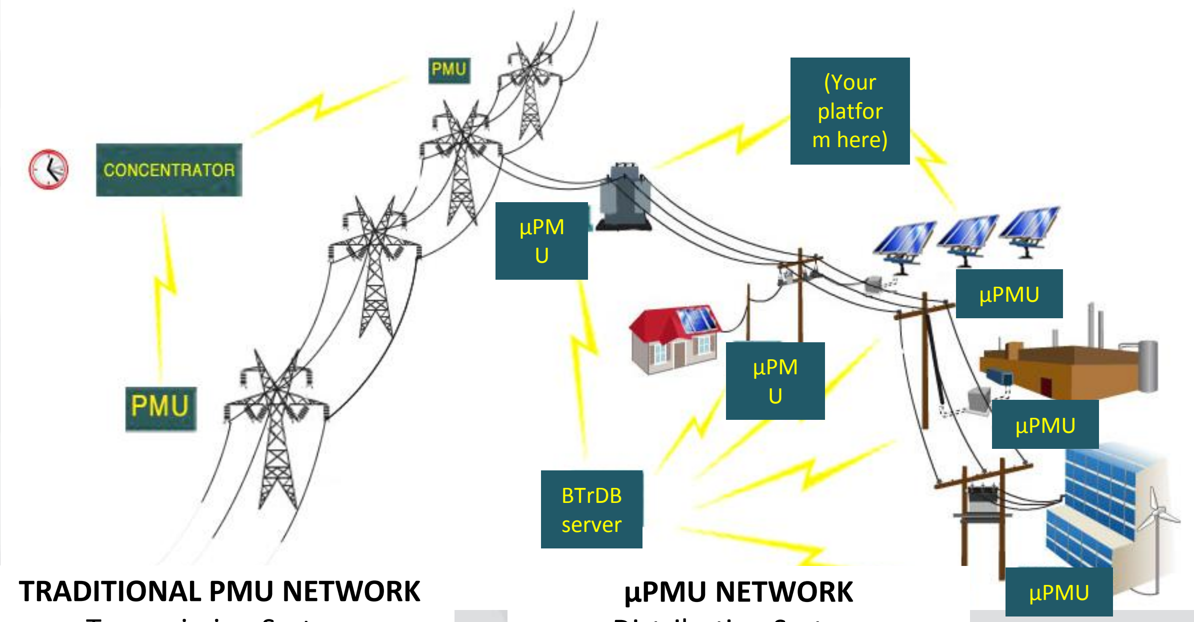
Courtesy NASPI



https://selinc.com/solutions/synchrophasors/

Micro-synchrophasor network concept:

Create visibility for distribution circuits behind the substation to support integration of distributed resources

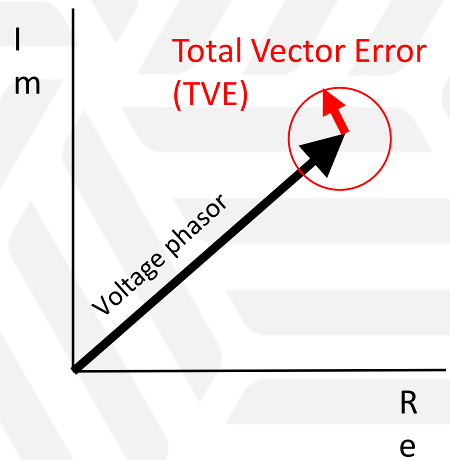


TRADITIONAL PMU NETWORK
Transmission System

µPMU NETWORK
Distribution System

Why PMUs mostly on transmission, not distribution systems to date?

- historically, no need (but this is changing):
  - unidirectional power flow, from substation to load
  - unquestioned stability of distribution system
- cost / value proposition
- more challenging measurements – fractions of a degree

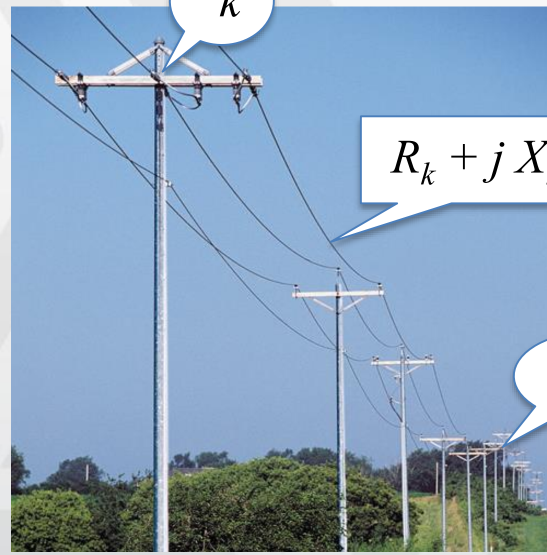


Transmission PMU performance ~ 1% TVE is not small enough for distribution: $\sin^{-1} 0.01 \approx 0.6^o$

Distribution systems are tricky…

$$P \approx \cancel{\frac{V_1 V_2}{X}} \sin \delta_{12}$$

this nice approximation doesn't work well



$$|V_{k-1}|^2 - |V_k|^2 \approx 2(R_k P_k + X_k Q_k)$$

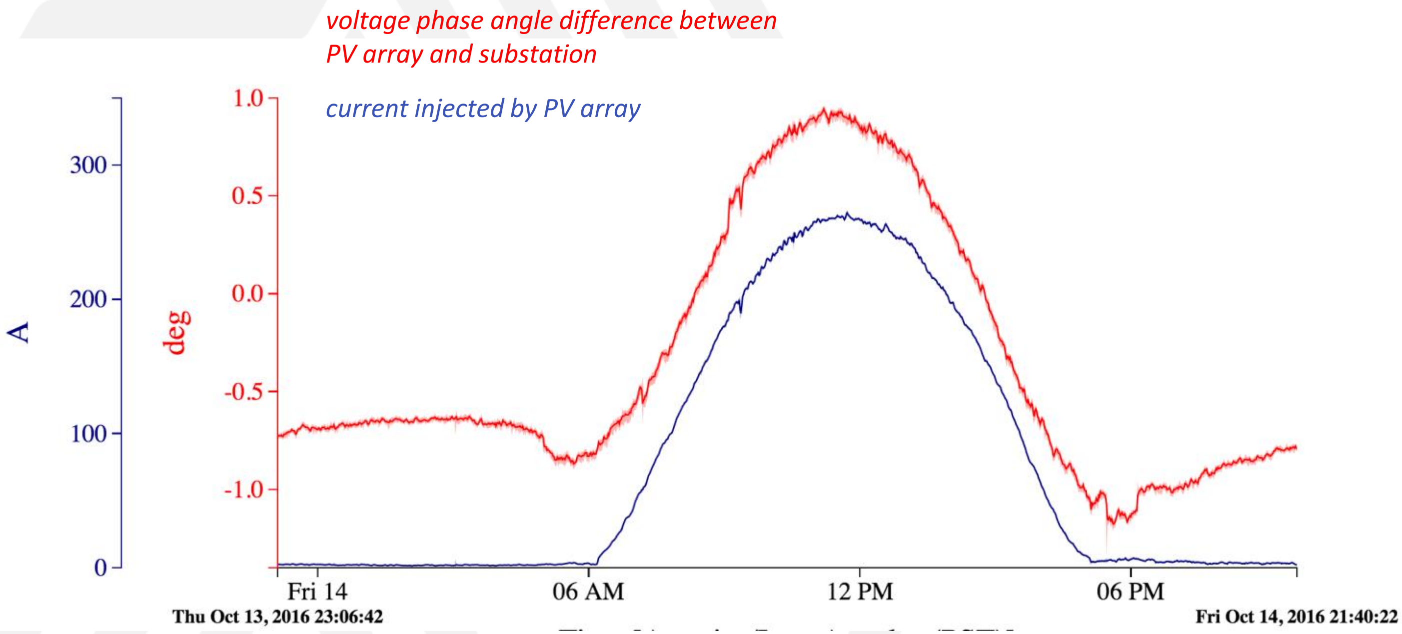
$$\delta_{k-1} - \delta_k \approx \frac{X_k P_k - R_k Q_k}{|V_k||V_{k-1}|}$$

both X and R show up in these expressions; P and Q are not decoupled like in transmission

Linear approximations derived from DistFlow equations for radial feeders by Dan Arnold, Roel Dobbe and Michael Sankur, UCB

…and this doesn't even include three-phase imbalance!

Illustration: Measured phase shift along 12kV distribution circuit




Grizzly Substation
feeds LBNL and UC Berkeley campus
115 kV from PG&E
12 kV distribution

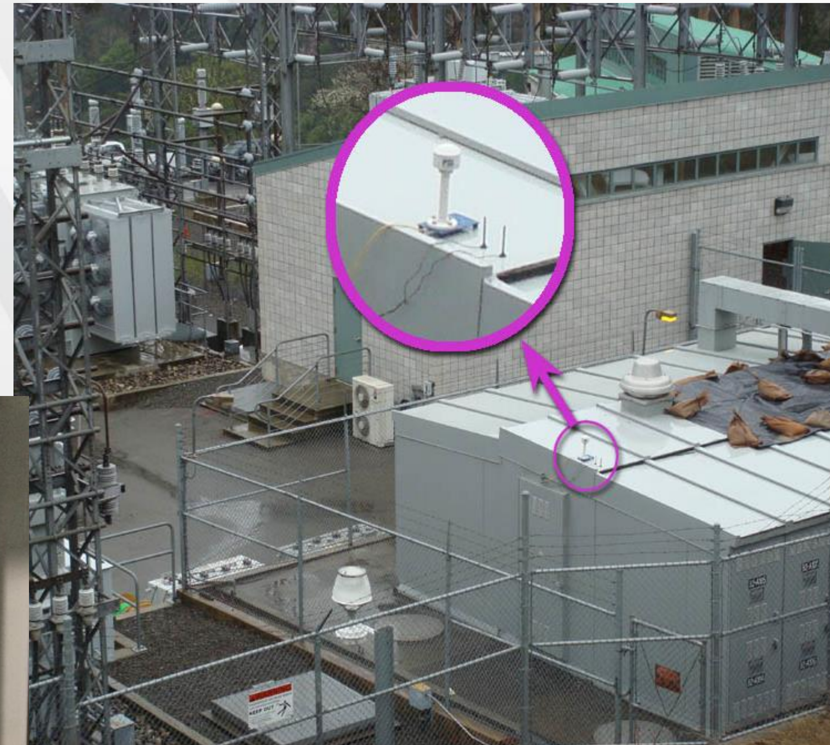
ARPA-E µPMU Project

Field installations:

UC Berkeley/LBNL

Southern California Edison

Riverside Public Utilities



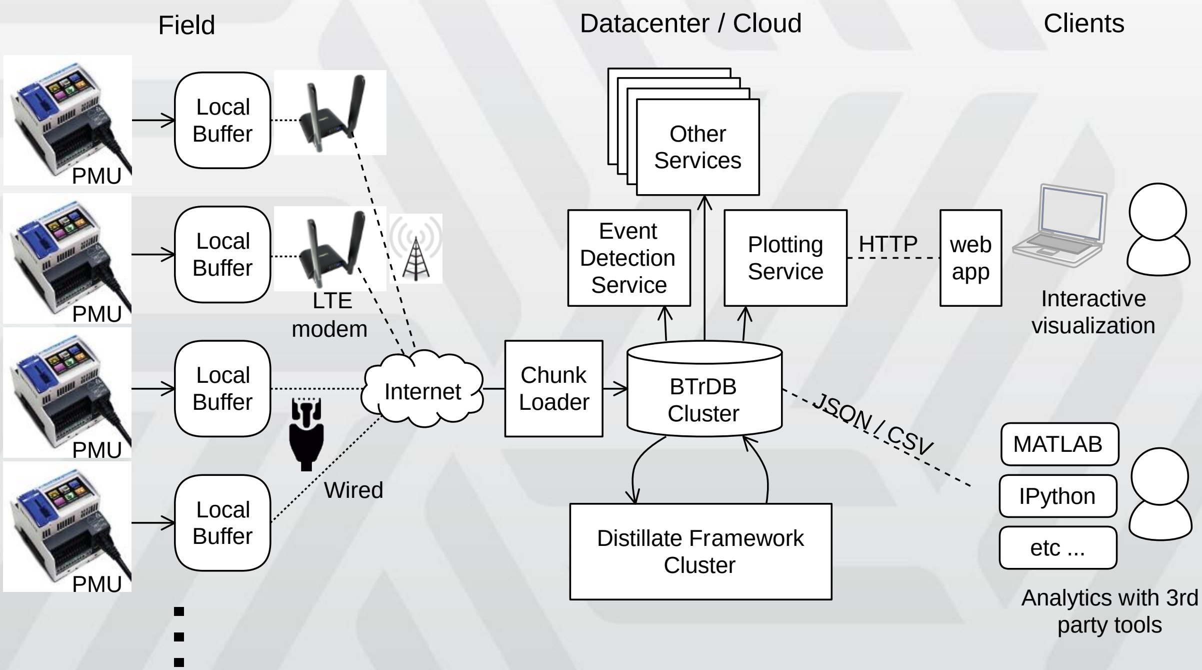
Alabama Power (Southern Co.)

Georgia Power (Southern Co.)

Tennessee Valley Authority

Pacific Gas & Electric Co.

Berkeley Tree Database (BTrDB)



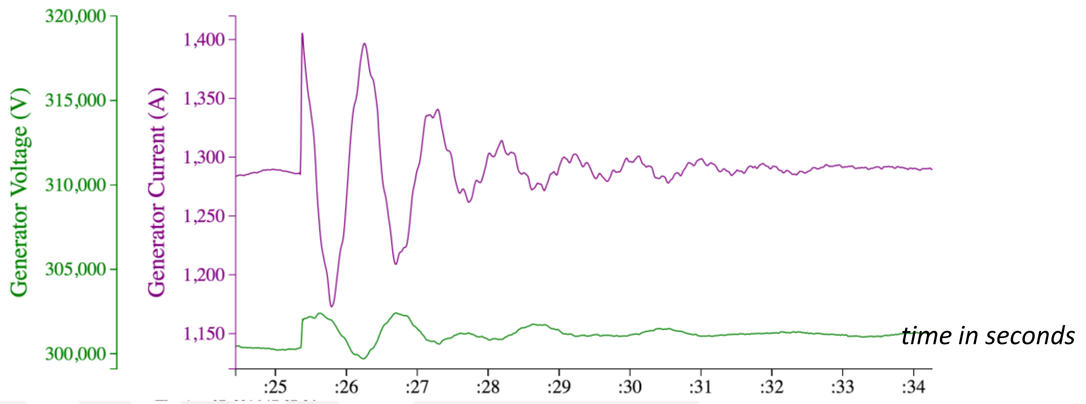
ARPA-E research project configuration: 40+ µPMUs sending 120 Hz data via Ethernet or 3G/4G wireless, 12 streams per device (voltage and current magnitude & phase angle)

Michael Andersen, UC Berkeley

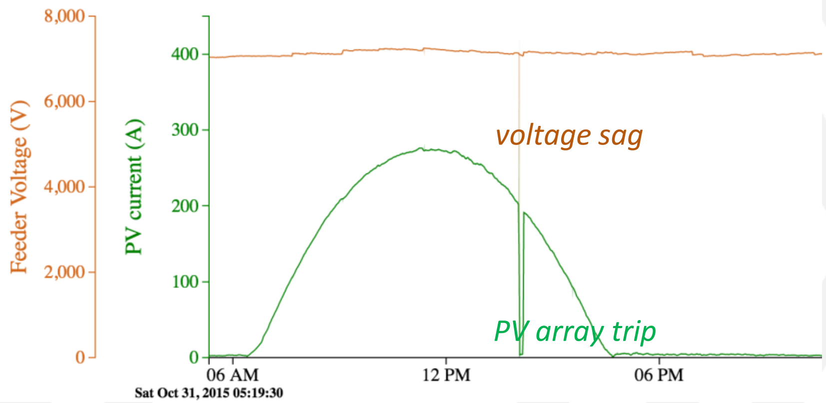
Use cases: Mitigating system vulnerability to disturbances

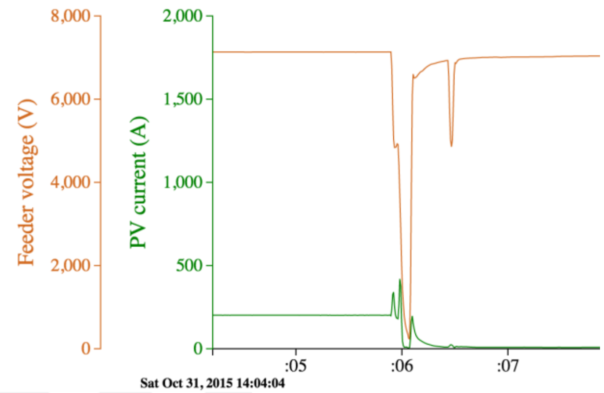
PMU data reveal dynamic response across transmission and distribution:

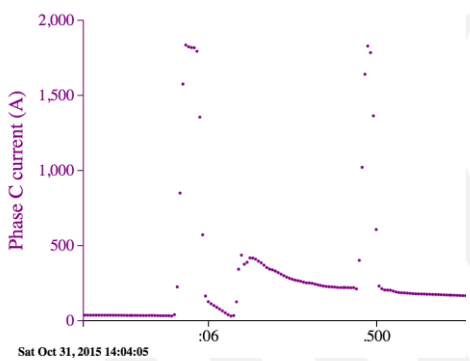
- assess stability operating limits
- identify exposure to large disturbances, e.g. geomagnetic (GMD)
- diagnose local control issues, oscillations
- understand implications of reduced system inertia with inverter-based generation: the design basis has changed



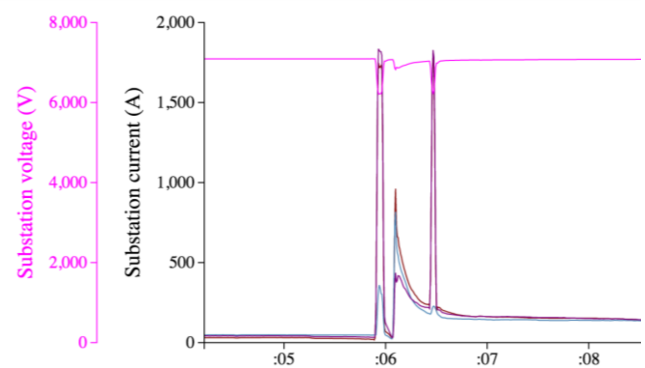
Use case example: Diagnose cause of DG unit trips



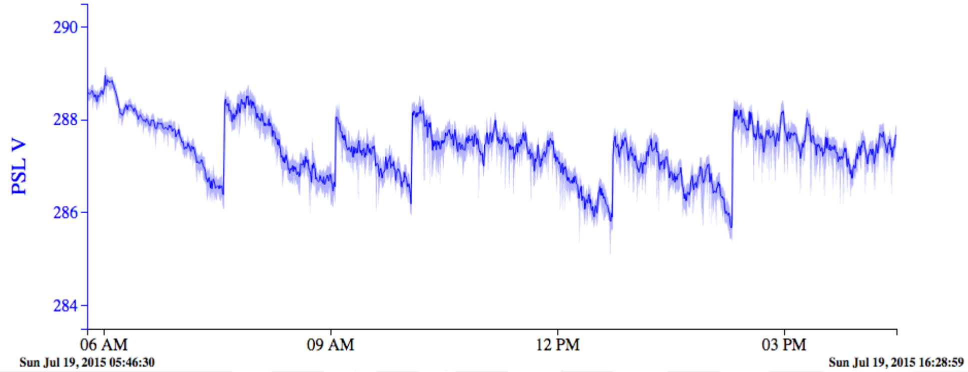




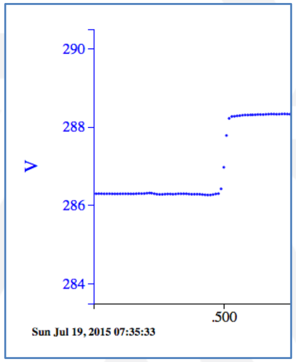
caused by phase B-C fault (palm frond contact)
down the feeder



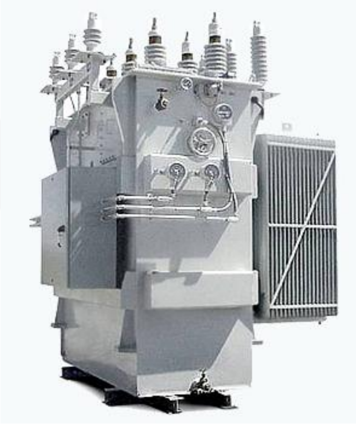
Use case: Detect normal and mis-operation of equipment



Tap changer at substation transformer steps voltage up as load increases over the course of the day

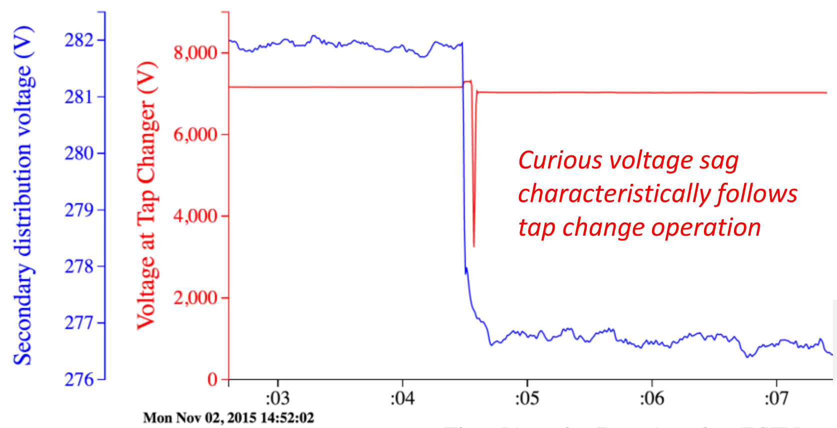


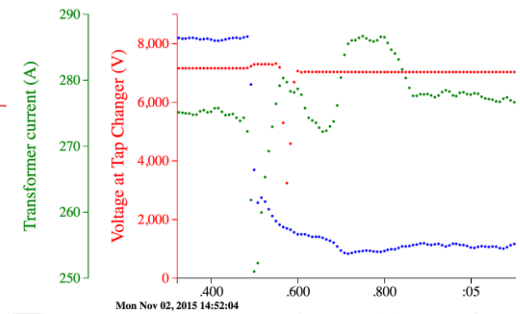
Example:
Anomaly in tap change signature can give early warning of transformer aging or incipient failure



Tap change occurs over ~2 cycles
Graph shows individual 120-Hz samples

Use case: Detect normal and mis-operation of equipment

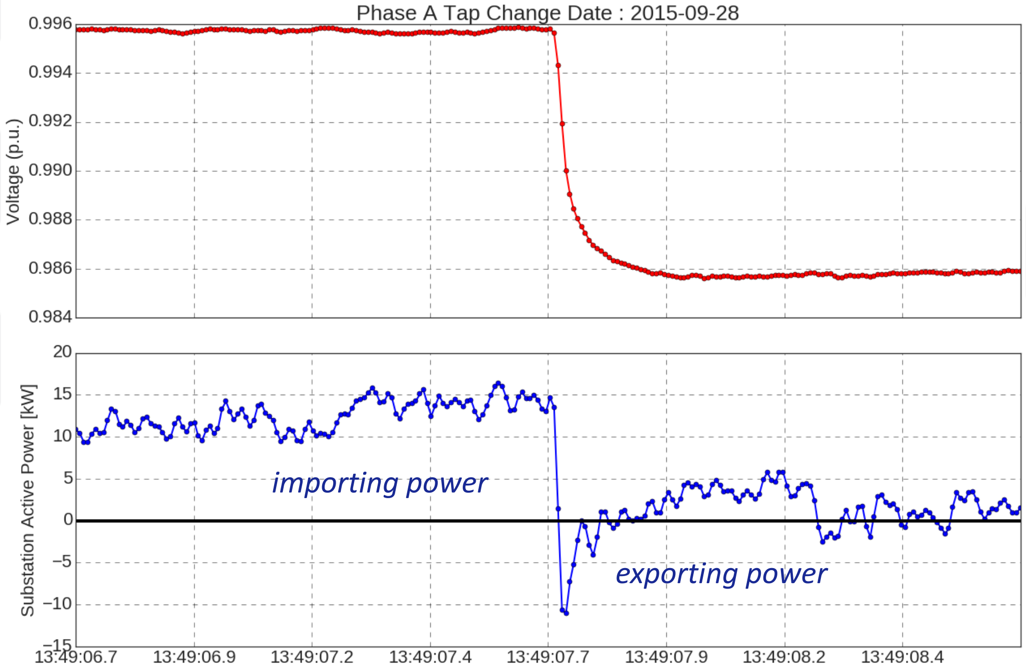




Example:
Anomaly in tap change signature gives early warning of transformer aging or incipient failure

Use cases: Feeder and load model validation, Reverse power flow detection

- Example: ascertain impacts of voltage regulation with hi-pen DG1.2% step down in voltage
- significant drop in kW due to highly voltage dependent load
- high-penetration solar PV feeder goes from net kW import to backfeed

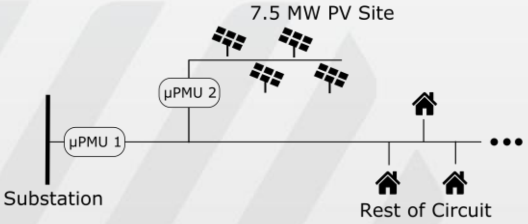


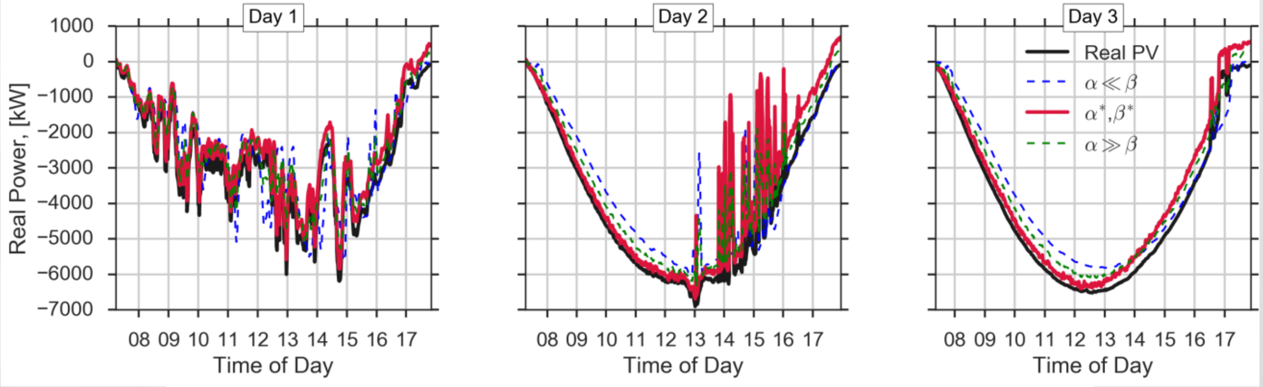
Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab

Use case: Disaggregating net metered DG from load

Customer-owned solar generation can mask an unknown amount of load, creating vulnerabilities for the system (e.g. simultaneous DG trips, cold load pickup).

µPMU measurements on the utility side of the meter offer an alternative to telemetry on customer premises or 3rd party data, to create awareness for operators.





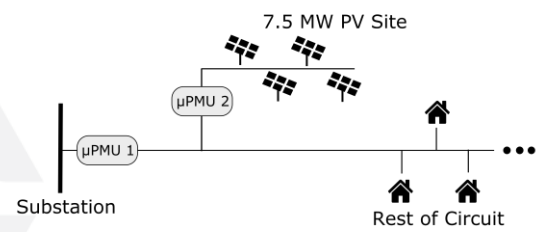
Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab

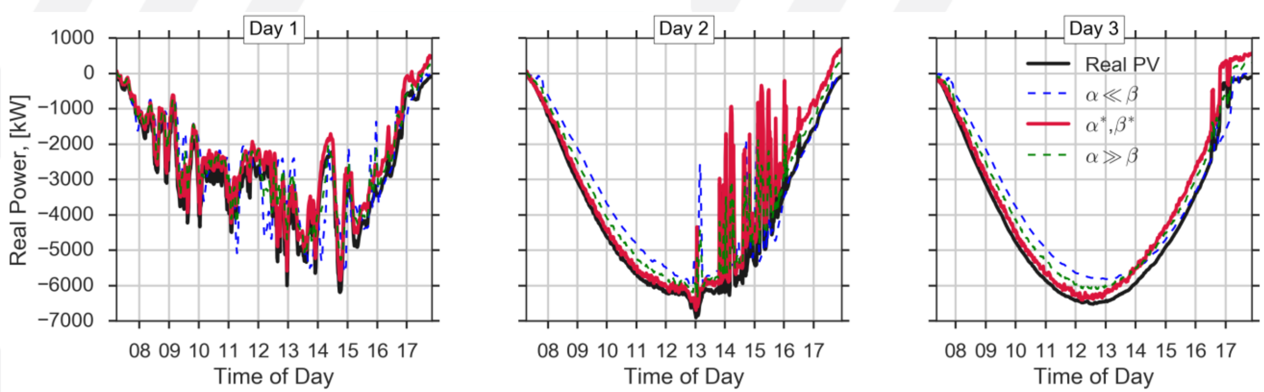
Use Case: Disaggregating net meterd DG from load

PV generation is estimated as a function of capacity, irradiance data and aggregate power measurement.

Model runs in real time to approximate actual performance of PV and identify masked load.

Test case: LBNL algorithm estimated actual PV generation (red) using only aggregate data from µPMU 1 and validated against direct PV measurement from µPMU 2 (black); performed within 6% RMSE over all sky conditions.





Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab

Incipient Failure Detection for Transformers (and other equipment)

- In the US – transformers are in general a big point of failure in the aging distribution system – when the fail, they cause an outage and $$ to replace
- Application picked up the signature below multiple times
  - Tap change followed by voltage sag – multiple times
  - We can only see this relational information with synchronized datasets from the uPMU
  - Tap changer oil leak – signature is evident before normal warning of failure